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# Effects of Weave Architecture on Aeroacoustic Performance of Ceramic Insulation Blankets

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## ABSTRACT

*A comparison of sewn, quilted Advanced Flexible Reusable Surface Insulation (AFRSI) blankets and integrally woven core Tailorable Advanced Blanket Insulation (TABI) systems was conducted in a 170 decibel aeroacoustic environment under oscillating air loads. Preconditioning in a radiant heat source was done at both 2,000°F and 2,500°F before testing. It was shown that a multilayer weave construction based on an angle interlock weave architecture was superior to other systems investigated and did not require a surface coating to enhance survivability. Single-ply TABI fabric surfaces using an insulated integrally woven core structure can survive up to 2,000°F without the use of a ceramic coating to toughen the surface to the aeroacoustic noise level. AFRSI blankets required a ceramic coating in order to demonstrate comparable performance after exposure to a 2,000°F radiant heat temperature.*

## INTRODUCTION

The consideration of flexible ceramic blankets as an external thermal protection system (TPS) for advanced space vehicles has gained acceptance since the adoption of Advanced Flexible Reusable Surface Insulation (AFRSI) as a TPS for the fleet of Shuttle orbiters. AFRSI is a sewn, quilted blanket assembly of silica fabrics, threads, and insulation in a sandwich-like format that offers thermal protection up to 1,200°F at modest aeroacoustic noise levels during ascent and reentry.[1-3] During the process of certifying AFRSI as a Shuttle TPS, a severe erosion of fabric and insulation occurred to the AFRSI blankets during the flight of STS-6 on the right orbiter maneuvering system (OMS) pod.[4] The next flight, STS-7, resulted in additional damage to the left OMS pod. A decision was made to toughen the AFRSI fabric surface with a coating to resist the air loads encountered by the space Shuttle. A ceramic coating was developed, tested, and certified as a surface coating for the AFRSI.[5] This coating, C-9, now coats about 4,000 square feet of the surface of the AFRSI blankets on each of the four Shuttle orbiters. This coating has eliminated the fabric and thread damage that occurred at specific locations on early flights of the Challenger vehicle.

Advanced space vehicles under study for future space exploration programs will probably operate at more severe aeroacoustic levels and higher aerothermal loads than the space Shuttle orbiters. The Space Exploration Initiative, the Single-Stage-to-Orbit, the Advanced Launch System, and the National Aerospace Plane are examples of programs that should consider advanced flexible ceramic TPS as part of their external insulation requirements. Integrally woven core concepts using silicon carbide fibers are now being used to design and fabricate a flexible ceramic TPS that can function at both higher temperatures and higher aeroacoustic loads. Various surface weave designs of these integrally woven core structures have been fabricated into a TPS called Tailorable Advanced Blanket Insulation (TABI). These threadless constructions have the top face fabric and bottom face fabric integrally connected by a rib structure during the weaving process.[6-8] The rib core or cell structure is then insulated by inserting a ceramic batting into the hollow core to form a TPS structure.

It was the objective of this study to determine the aeroacoustic survivability of flexible ceramic blankets in a fluctuating aerodynamic loads environment. Both the sewn, quilted blankets (AFRSI), and the integrally woven core blankets (TABI) were studied in a specially designed miniwind-tunnel test facility (MWTF). The MWTF was originally designed to investigate the causes of failure of the AFRSI blankets that occurred during Shuttle flight STS-6.[9-10] The test facility used a small test article that permitted the evaluation of a large number of experimental ceramic blanket constructions. This paper focuses on the resistance of surface weave architecture to high noise levels in a pulsating aerodynamic environment. The previous tests with the MWTF suggested its use as a screening test for ceramic blankets exposed to overall sound-pressure levels (OASPL) up to 170 decibels in an oscillating-pressure environment.

## MATERIALS AND EXPERIMENTAL PROCEDURES

### Materials

Two distinct construction methods were employed to fabricate the flexible ceramic blankets evaluated for this study. The first method used a sewn, quilted blanket construction which sandwiched the components together using a sewing thread (Figure 1). These blankets are referred to as the AFRSI

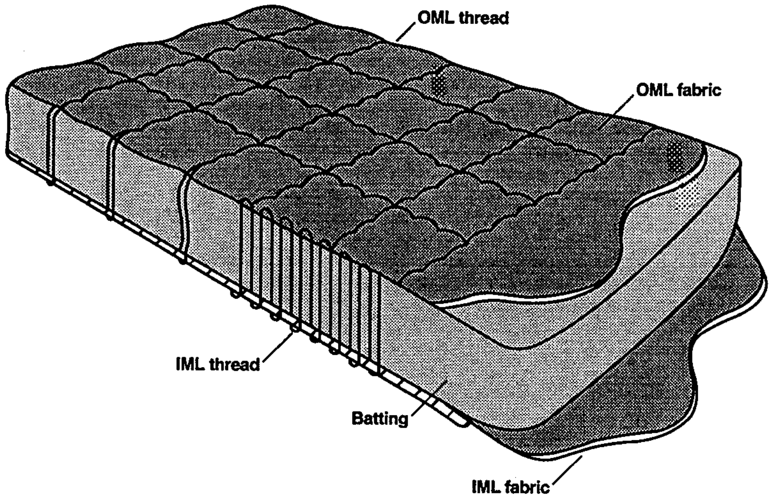


**Figure 1.** Advanced Flexible Reusable Surface Insulation (AFRSI) Blanket.

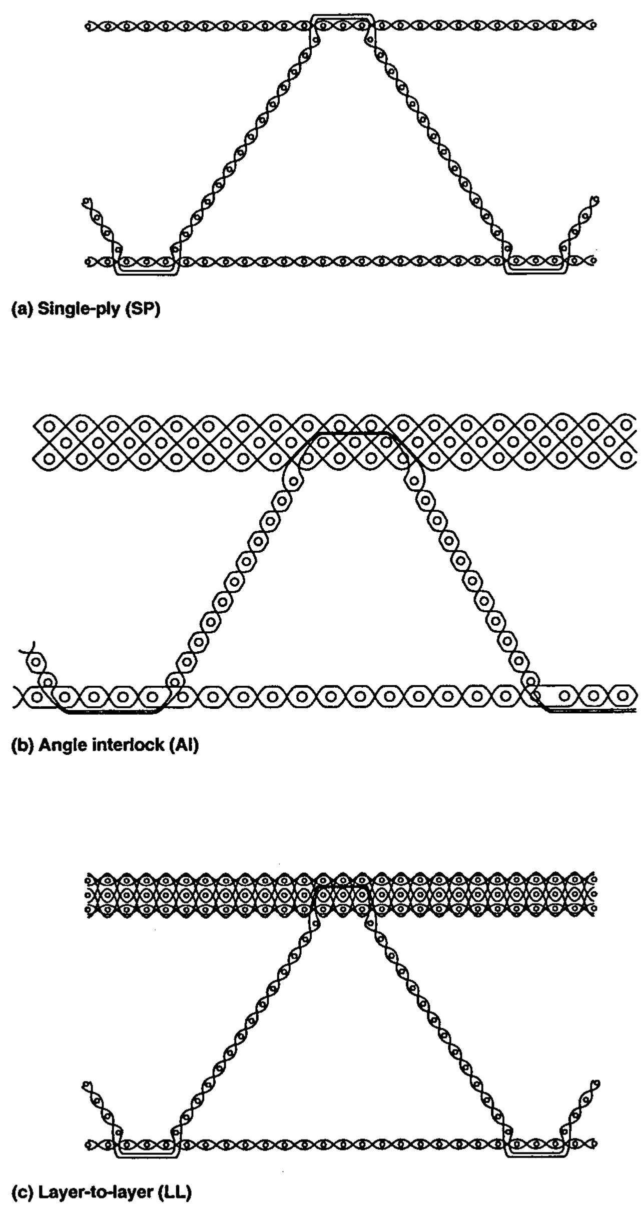


**Figure 2.** Schematic of Tailorable Advanced Blanket Insulation (TABI) weave. (a) Single-ply (SP); (b) Angle Interlock (AI); and (c) layer-to-layer (LL).

versions. Two different AFRSI systems were studied. The first, uncoated AFRSI, uses a silica-based system both as the outer mold line (OML) fabric and thread. This system was exposed to the aerothermal environment and was successfully flown on seven flights of the OV-099 (Challenger) space Shuttle vehicle.[4] The second TPS system examined was a C-9 coated AFRSI blanket that currently functions as a certified flight TPS on the fleet of four Shuttle orbiters. This is the same as the uncoated AFRSI, except the OML surface is coated with the C-9 coating reported in Reference 5.

The second type of TPS construction evaluated was based on an integrally woven core structure where the surface weave architecture varied from a single-ply fabric surface to two different multilayer fabric surfaces based on an angle interlock and a layer-to-layer integral woven surface. The threadless TPS's are referred to as TABI-SP, for the single ply surface, TABI-AI for the angle interlock woven surface, and TABI-LL for the layer-to-layer woven surface. All of these constructions used silicon carbide yarn for the woven surfaces. A schematic of the three surface-weave styles is illustrated in Figure 2. The longitudinal core is woven in the form of a triangular cell. In all cases, the surface fabric is woven as an integral part of the total weave design.

### Radiant Heat Exposure Test

A radiant lamp test apparatus operated at atmospheric pressure as reported in Reference 11 was used to precondition all test articles. The primary purpose of this procedure was to expose the surface fabric of the different TPS constructions to a surface conditioning temperature prior to any acoustic exposure. Temperatures of 1,200°F, 2,000°F, and 2,500°F were used depending on the particular ceramic fabric. Exposure times were 10 minutes at 1,200°F, 2 minutes at 2,000°F, and 2 minutes at 2,500°F. All the test articles were cooled to room temperature before being remounted into the aeroacoustic test configuration. Also, the sample size (6.5 inches by 7.5 inches long by 1.0 inch deep) was the same for both the radiant heat test and the mini-wind-tunnel test facility, which minimized handling and

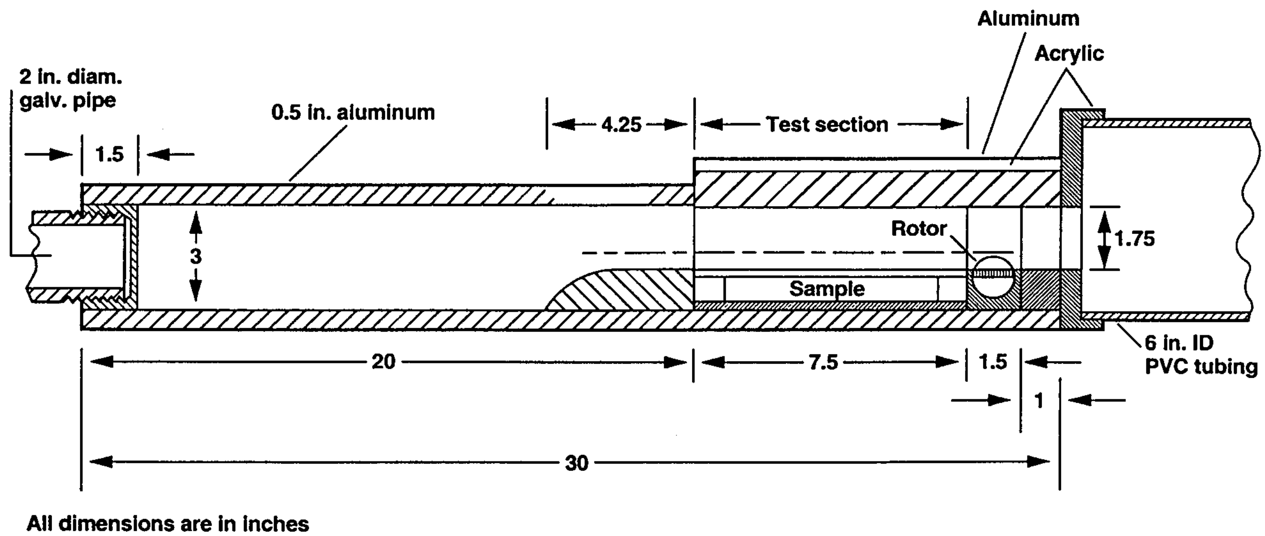


**Figure 3.** Sketch of mini-wind-tunnel test (MWTF) apparatus [10].

mounting damage to the ceramic blankets being evaluated.

### Mini-Wind-Tunnel Test Facility (MWTF)

Aeroacoustic testing was conducted in a small wind tunnel apparatus specifically designed to simulate oscillating air loads on the surface of the AFRSI or TABI articles. A full description of the design, operational, and performance characteristics are detailed in References 9 and 10. This MWTF provided the advantage of small sample size, rapid start or stop capability, constant visual observation, and excellent control of aerodynamic conditions. For this study, all test articles were exposed to a dynamic pressure of 510 pounds per square foot, a total pressure setting of 6 pounds per square inch, a fluctuating pressure of 2.7 pounds per square inch, and an overall sound pressure level of 170 decibels. The surface area exposed to this condition was 3.5 inches by 5 inches. Typically, the TABI test panels had three complete cores exposed to this environment in the parallel direction and at least four complete cores tested in perpendicular flow direction. Also, a rotor speed of 100 revolutions per second was selected because of the superior waveform and amplitude measured at this condition. Prior to insertion of the test article into the MWTF, a calibration panel was inserted into the test section to simulate the entry-like aerodynamic conditions indicated. A schematic of the MWTF is shown in Figure 3.

## RESULTS AND DISCUSSION

### Advanced Flexible Reusable Surface Insulation (AFRSI) Blankets

Both the uncoated AFRSI and the C-9 coated AFRSI blankets were exposed to a radiant heat-lamp source. Three radiant heat conditions were selected for the two AFRSI blanket systems including 10 minutes at 1,200°F, 2 minutes at 2,000°F, and 2 minutes at 2,500°F. This provided a heat treatment to the fabric surface of these blankets prior to testing in the MWTF. The AFRSI are constructed from the silica materials as shown in Table 1 and represented the state-of-the-art in quilted ceramic blankets used as external TPS for the Space Shuttle. Figure 4 represents the results of the aeroacoustic exposure conducted.

An arbitrary performance criteria based on increasing durability to a 170 decibel noise level after exposure to a radiant heat source was selected using a visual inspection method of interpreting the performance. The test was terminated after 600 seconds if no damage occurred during the exposure period. The criteria, ranked in order of decreasing damage to the fabric surface, were obtained by observation during testing in the MWTF. The ability to instantly stop the aerodynamic flow of air across the test article provided an accurate picture of the failure mode in real time. As shown in Figure 4, the C-9 coated AFRSI, which is the certified blanket TPS for the fleet of Shuttle vehicles, experienced no damage at an aeroacoustic noise level of 170 decibels after exposure to 1,200°F radiant heat for 10 minutes. It also

| Sewn, Quilted Blanket | OML Fabric | OML Thread | Insulation | Coating |
|---|---|---|---|---|
| Uncoated AFRSI | Silica | Silica | Silica | None |
| Coated AFRSI | Silica | Silica | Silica | C-9 |

| Integrally Woven Core Blanket | Yarn | Insulation | Face Fabric Style |
|---|---|---|---|
| TABI-1800 SP | 1800 Denier silicon carbide | Silica | Single-ply plain weave |
| TABI-600 SP | 600 Denier silicon carbide | Alumina | Single-ply plain weave |
| TABI-600 AI | 600 Denier silicon carbide | Alumina | Angle-interlock |
| TABI-600 LL | 600 Denier silicon carbide | Alumina | Layer-to-layer |

**Table 1.** Flexible ceramic thermal protection system (TPS) construction.

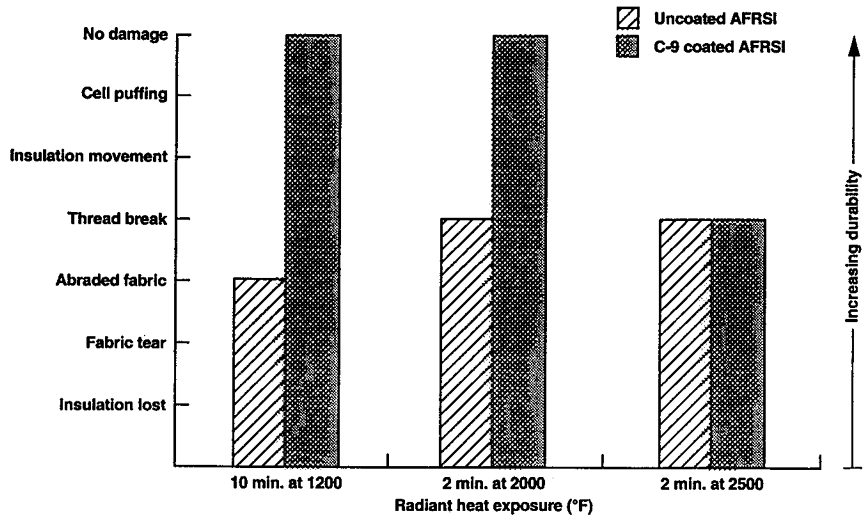


**Figure 4.** Aeroacoustic behavior of AFRSI blankets at 170 decibels in MWTF.

showed no damage to the aeroacoustic test environment after exposure for 2 minutes at 2,000°F. Only after exposure to 2 minutes at 2,500°F was the C-9 coated AFRSI damaged. In this instance, the test was terminated after 15 seconds due to stitch thread breakage. This was first seen after 3 seconds with additional stitches breaking (a total of 5 threads) up to the 15 second time of stoppage. This represents a failure because, if the test continues, propagation of damage results in fabric abrasion and is followed by fabric tearing and, finally, the catastrophic loss of insulation. All the uncoated AFRSI blankets similarly tested failed, as represented in Figure 4. Broken threads or fabric abrasion were the reasons for early termination in these situations. Thread breakage was noticed in 1 to 11 seconds and fabric abrasion observed between 13 and 35 seconds. These observations show that surface toughening or densification of the fabric surface of AFRSI by the application of a ceramic coating does provide a quilted blanket TPS that is more resistant to high aeroacoustic noise (170 decibels) under fluctuating air loads than the uncoated AFRSI blanket after a 2,000°F exposure to a radiant heat lamp for 2 minutes. After the 2,500°F exposure condition, both the C-9 coated AFRSI and the uncoated AFRSI suffered the same broken thread damage when tested in the MWTF environment. At 2,500°F, the silica fibers and C-9 coating tend to embrittle even after short radiant heat conditioning.

## Tailorable Advanced Blanket Insulation – Integrally Woven Core Structures

### *Comparison of TABI-1800 SP and TABI-600 SP.*

The TABI-1800 SP was constructed using an 1800 denier silicon carbide yarn to weave a triangular core structure having a single-ply, plain-weave face fabric as a

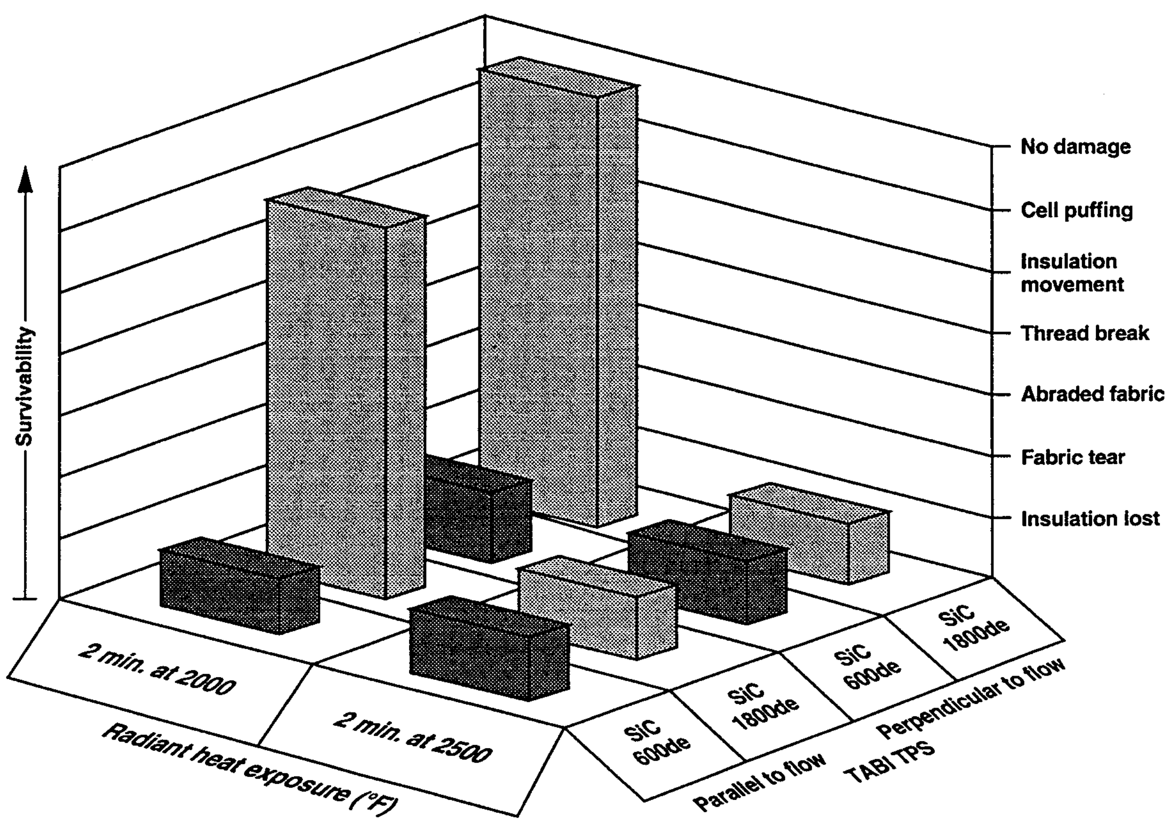


**Figure 5.** Aeroacoustic survivability of 1800 denier silicon carbide yarn TABI compared to 600 denier silicon carbide yarn TABI at 170 decibels.

| TABI | Fiber Diameter, mm | Face Fabric Thickness, in | Yarn Density | | Filaments/ Strand | Crimp Factor, % |
|---|---|---|---|---|---|---|
| | | | Warp, epi | Fill, ppi | | |
| 1800 denier silicon carbide, single-ply | 15 | 0.017 | 16.0 | 24.0 | 500 | 8 |
| 600 denier silicon carbide, single-ply | 12 | 0.009 | 28.0 | 29.0 | 250 | 3.5 |
| 600 denier silicon carbide, angle-interlock | 12 | 0.032 | 112.0 | 83.5 | 250 | 9.5 |
| 600 denier silicon carbide, layer-to-layer | 12 | 0.029 | 112.0 | 61.5 | 250 | 7.5 |

**Table 2.** Flexible ceramic thermal protection system (TPS) construction.

part of the integrally woven structure. In this case, the hollow cores or cells were filled with silica insulation. Test articles were prepared having the core length oriented both parallel and perpendicular to the aerodynamic flow. Prior to aeroacoustic testing, one set of test articles was exposed to a radiant heat source for 2 minutes at 2,000°F. Another set was conditioned to the radiant heat source for 2 minutes at 2,500°F. Each individual test panel was exposed to the aeroacoustic test environment reported in the Materials and Experimental Procedures section. The results are shown in Figure 5. The test panel oriented perpendicular to the airflow after the 2,000°F radiant heat exposure, experienced no damage after 600 seconds. The test was arbitrarily terminated because this appears to represent a reasonable flight profile a TPS could be expected to endure. Another TABI-1800 SP panel with the cell orientation directed parallel to the airflow showed a puffing of three cells near the leading edge after 30 seconds. This indicated that the insulation moved in the airflow direction creating a shallow spot in the insulated cell. The test was continued to 600 seconds with no further degradation observed. The pair of TABI-1800 SP test panels preconditioned to the 2500°F radiant heat source were also tested in the MWTF. Both the parallel and perpendicular orientation of the TABI core direction to the airstream failed almost instantaneously (within 2 seconds). One cell of the parallel mounted panel was partially destroyed with the fabric torn and the silica insulation lost into the air stream. Three of the four cores of the perpendicular mounted TABI-1800 SP panel were destroyed in a similar fashion.

The TABI-600 SP was prepared from a 600 denier silicon carbide yarn into a construction similar to the TABI-1800 SP. For comparison, one TABI-600 SP panel and one TABI-1800 panel were mounted with the cells oriented parallel to the air flow; a second set of panels was mounted perpendicular to the airflow. The results of the aeroacoustic testing after the radiant heat exposure are shown in Figure 5. After the 2,000°F radiant heat exposure, the test panels with the core direction parallel to the airflow pillowed (puffed) in 60 seconds, followed by catastrophic failure at 158 seconds when the fabric tore and the insulation in the three parallel cores exposed to the test environment was blown away. The test panels in the perpendicular orientation experienced a pillowing across the cell near the leading edge in about 25 seconds, followed by complete failure at 129 seconds in the same cell region. Next, the TABI-600 SP was tested at the same aerodynamic conditions after the 2 minute radiant heat treatment at 2,500°F. Within 2 seconds fabric tearing followed by removal of insulation in the breached fabric cell area was observed whether the cell direction was parallel or perpendicular to the airflow direction.

In comparing the aeroacoustic survivability of these two single-ply, plain-weave TABI systems, the influence of the face fabric surface weave geometry exposed to a fluctuating air load impinging the surface at an OASPL of 170 decibels must be considered. Table 2 summarizes the key fiber and weaving properties that might impact the aeroacoustic behavior of these integrally woven blanket systems. The TABI-1800 SP yielded a linear yarn density lower than the TABI-600 SP. Nevertheless, the 1800 denier yarn produces a larger fiber bundle than the 600 denier silicon carbide yarn because of the larger fiber diameter (15 mm versus 12 mm) combined with twice the number of filaments per strand (500 versus 250). This results in a tighter weave construction, greater face fabric thickness (0.017 inches versus 0.009 inches) and less porosity for the TABI woven from the 1800 denier yarn. This may explain the ability of the 1800 denier woven yarn to survive the fluctuating air loads at 170 decibels after a 2,000°F preconditioning for 2 minutes in a radiant heat source. Apparently, the higher crimp factor obtained during the weaving process for the 1800 denier silicon carbide yarn did not degrade the filaments sufficiently to cause a failure. However, as seen in Figure 5, both TABIs failed in the same environment after a 2,500°F radiant heat preconditioning, even though all of the panels had the same weave characteristics. Previous strength and flexibility studies of silicon carbide yarns and fabrics have shown a drop in strength retention and bending ability at temperatures above 2,200°F.[12-13] In addition, a recent study has demonstrated that the formation of an oxide layer thickness that grows with increasing temperature may contribute to the loss of strength properties at elevated temperatures.[14] Since the TABI constructed from the 1,800 denier silicon carbide yarn failed at 2,500°F, but not at 2,000°F, these studies offer an explanation of why the survival of single-ply face fabrics in an oscillating air load at 170 decibels is limited to 2,000°F temperature for the 1,800 denier silicon carbide woven system.

### *Comparison of TABI-AI and TABI-LL*

Both the TABI-AI and the TABI-LL have complex weave geometries that could influence the aeroacoustic properties of flexible ceramic TPS. Both the TABI-AI and TABI-LL were woven with 600 denier silicon carbide yarn. The integration of a multilayer surface-weave architecture, such as the angle interlock and the layer-to-layer, as part of the TABI weave pattern might stabilize the fabric surface to the oscillating air loads by reducing, flutter and porosity. As was done previously, two sets of TABI-AI and two sets of TABI-LL were prepared with the core direction in one set parallel to and the other set perpendicular to the airflow when mounted in the test frame. One set was preconditioned for 2 minutes at 2,000°F and the other set for 2 minutes at 2,500°F in a radiant heat source. Both the angle-interlock surface (TABI-AI) and the layer-to-layer surface (TABI-LL) showed no damage upon exposure to the aeroacoustic test environment after the 2,000°F radiant heat preconditioning in either the parallel or perpendicular cell orientation. The tests were stopped at 600 seconds. No cell puffing or insulation movement was observed. These observations are presented in Figure 6.

Next, the TABI-AI and the TABI-LL that had been exposed to the 2,500°F radiant heat were tested in the MWTF. For this case, a significant difference was observed, as shown in Figure 6. The TABI-AI suffered no damage or any other observable transient defect regardless of core direction (parallel or perpendicular) to the airflow after a 600 second test duration. The TABI-LL, tested at the same test condition, suffered rapid destruction (within 2 seconds) near the leading edge of the airflow whether the core direction was parallel or perpendicular to the airflow. The test was repeated with the same negative results. The TABI-AI with the parallel oriented cores was tested up to a cumulative test time of 3,600 seconds (1 hour) with no detectable change in the surface.

The TABI-AI is aeroacoustically better than the TABI-LL after the 2,500°F radiant heat conditioning. The differences between the angle-interlock weave construction and the layer-to-layer weave construction might explain the superior performance of the TABI-AI after higher temperature conditioning. The TABI-AI has an angle-interlock surface weave comprised of four warp-yarn layers and three fillyarn layers where the warp yarn passes through the thickness of the fabric and returns to the outer surface. The warp yarns are also woven perpendicular to the core (flute) direction along an angled path. This produces a smooth and tightly woven face fabric. In addition, the higher crimp factor can result in lower porosity as well. The TABI-LL warp yarns are woven normal to the three fill layers, but do not pass through the entire thickness. The connecting warp yarns that interlock the outer fill layers to the middle fill layer are all woven in a plain-weave fashion. The layer-to-layer weave architecture produces a more rigorous interlacing at a more severe bending angle at the top, middle, and bottom fill layers than the angle-interlock weave. It can be expected that more individual filament breakage during weaving will occur, which causes the fabric surface to abrade or tear when stressed or fluttered. This is further aggravated at elevated temperatures where strength loss occurs.

## SUMMARY

The AFRSI blankets can perform up to 2,000°F if a ceramic coating is applied to the single-ply fabric surface as a means of surface stiffening and reducing the fabric porosity through surface densification. Above 2,000°F, the thermal stability of the silica-based system is exceeded.

The aeroacoustic performance of the different surface weave architecture studies revealed real distinctions in the capability of TABI to survive a high level of aeroacoustic noise under oscillating air loads. Figure 7 provides a summary of the durability of the TABIs

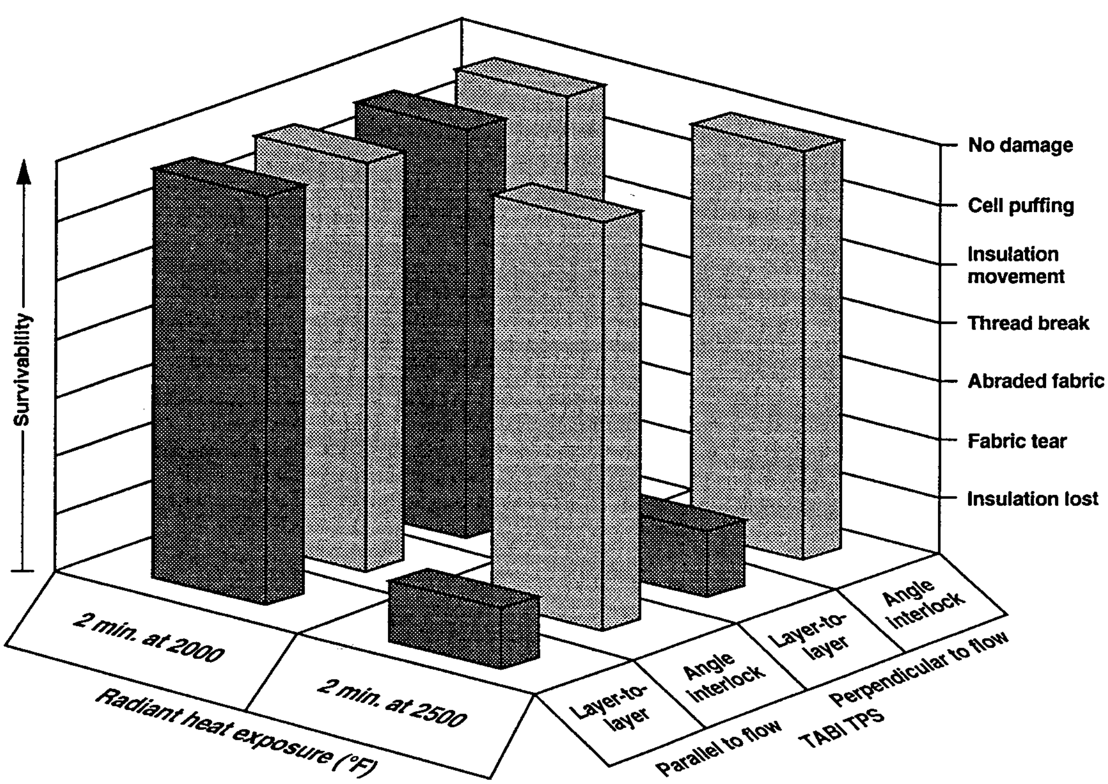


**Figure 6.** Aeroacoustic survivability of layer-to-layer TABI compared to angle-interlock TABI at 170 decibels.

that were first subjected to a preconditioning radiant heat source. The TABI-1800 SP, TABI-AI, and the TABI-LL incurred no observable surface fabric damage in either the parallel or perpendicular cell direction to the airflow after the 2,000°F radiant heat preconditioning. However, post test examination of the TABI-1800 SP showed the insulation in the parallel oriented cells had puffed near the leading edge, thus creating a shallow spot forward of this region. This anisotropic behavior of the parallel cell orientation to the flow direction could be a negative factor in thermal insulation effectiveness by requiring the TABI-1800 SP to be oriented perpendicular to the air stream on a vehicle. The TABI-600 SP was completely damaged in both orientations. Only the TABI-AI survived the aeroacoustic conditions after the 2,500°F radiant heat preconditioning. Additionally, the TABI-AI was successfully independent of cell orientation (isotropic) to the air stream since no insulation movement resulted that puffed or expanded the cell structure. The TABI-1800 SP and the TABI-LL did not survive this test condition. None of the TABI blankets required the use of a ceramic coating to protect the fabric surfaces.

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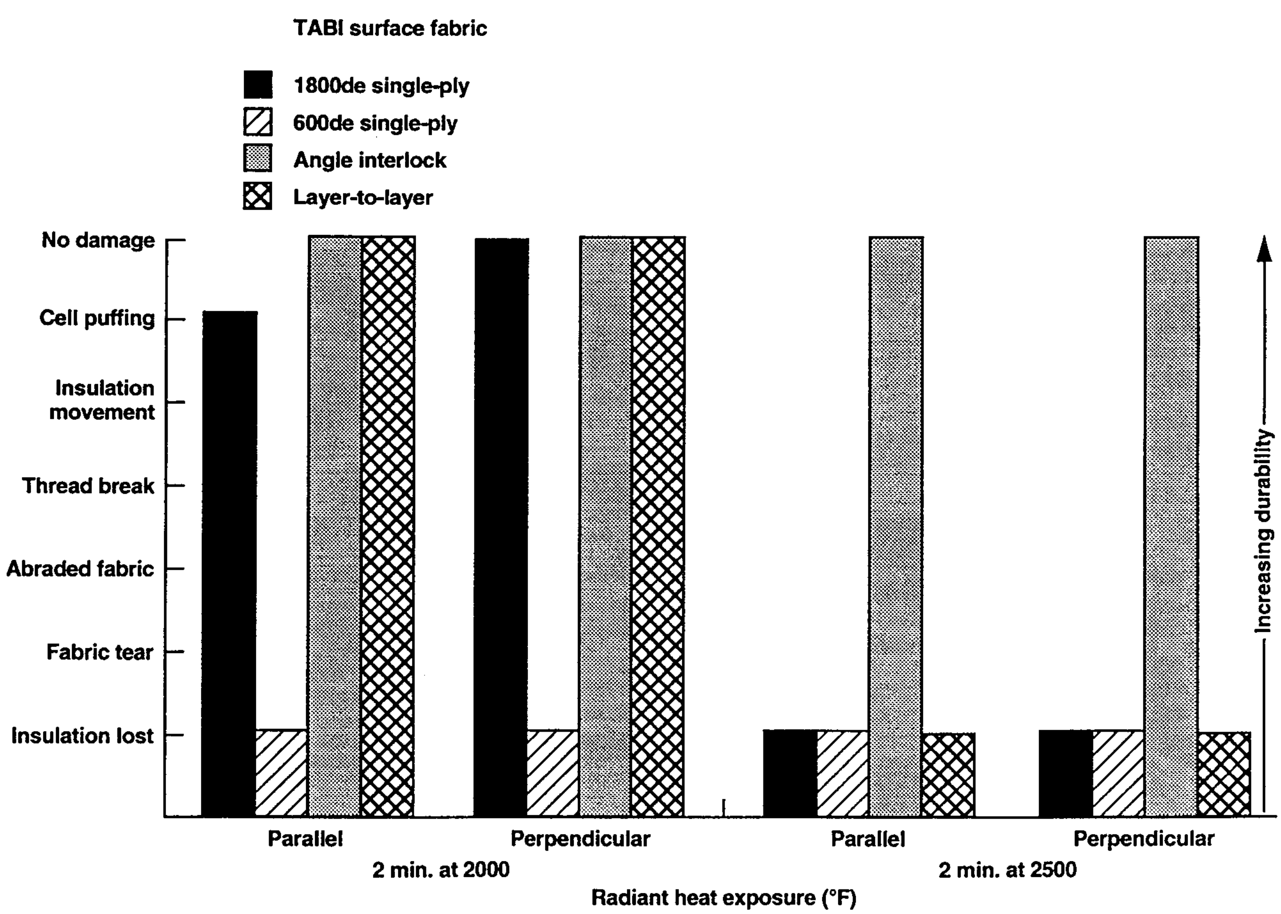


**Figure 7.** Comparison of silicon carbide TABI cell orientation to airflow at 170 decibels.